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NAVAL INTELLIGENCE SUPPORT CENTER
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4301 SUITLAND ROAD
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AUTHOR(S) 10 L. F. Kalitiyevskiy, L. F.

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THEORETICAL FUNDAMENTALS OF AIRCRAFT

THE EFFECT OF TRANSLATIONAL VELOCITY ON THE AERODYNAMIC CHARACTERISTICS OF AN AIR CUSHION VEHICLE

L. F. Kalitiyevskiy

Most works in the field of the theoretical investigation of air cushion vehicles (ACV) have been devoted to studying ACV functioning in the hover regime and only a few of them illuminate questions related to the translatory movement of ACV at high velocity. In this case, many of the works are experimental and we only encounter analytical methods of investigation in works [1 and 2].

The effect of translational velocity on the aerodynamic characteristics of a nozzle type air cushion vehicle is investigated in this article. As before [3], the jet flowing out of the nozzle of the ACV is assumed to be nonviscous, incompressible and quite thin. A plane-circularly shaped nozzle with zero deflection and a certain angle γ_c greater than zero is examined.

Obviously, in the former case the problem pertains to investigating flow-around of a cylindrical jet flowing against a screen, and in the latter the subject will be a conical, annular jet.

We take the coordinate system shown in Figure 1. We replace the jet with its midline and we shall characterize the edge of the jet in each cross-section by radius value r and angle Θ. We shall designate the discharge velocity from the nozzle W_0 and the velocity components on the edge of the jet - v_r and v_Θ respectively.

We shall assume that an incoming flow flows past the annular jet the same as a solid body with the cross-sectional shape of the jet. Then the distribution of pressure on the edge of the jet will coincide with the distribution of pressure on the surface of a solid body whose shape is similar to that of the jet. Such a method of solution was developed by M. S. Volynskiy and G. N. Abramovich and is widely used [for example, see (4)] .

Assuming flow in the jet and jet flow-around to be potential, the function of the velocity potential is written in the following form:

$$\varphi = \sum_{m=1} a_m^n(r) y^m \cos n\theta - W_0 y. \tag{1}$$

This function should satisfy the continuity equation

$$\frac{\partial^2\varphi}{\partial y^2} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2}\right). \qquad (2)$$

From (1) and (2), we obtain

$$m(m-1)a_m^n y^{m-2}\cos n\theta + \frac{d^2a_m^n}{dr^2}y^m\cos n\theta + \frac{1}{r}\cdot\frac{da_m^n}{dr}y^m\cos n\theta - \\ -\frac{n^2}{r^2}y^m\cos n\theta = 0.$$

Subsequently, we limit ourselves to a case m = 2 and n = 10. Then

$$a_1^0 = a_0 = const,\ a_1^1 = a_1 r,\ a_1^2 = a_2 r^2,\ a_1^3 = a_3 r^3,\ a_1^4 = a_4 r^4,\ \ldots,\ a_1^{10} = a_{10} r^{10};$$
$$a_2^0 = a^2 = a_2^4 = a_2^6 = a_2^8 = a_2^{10} = 0.$$

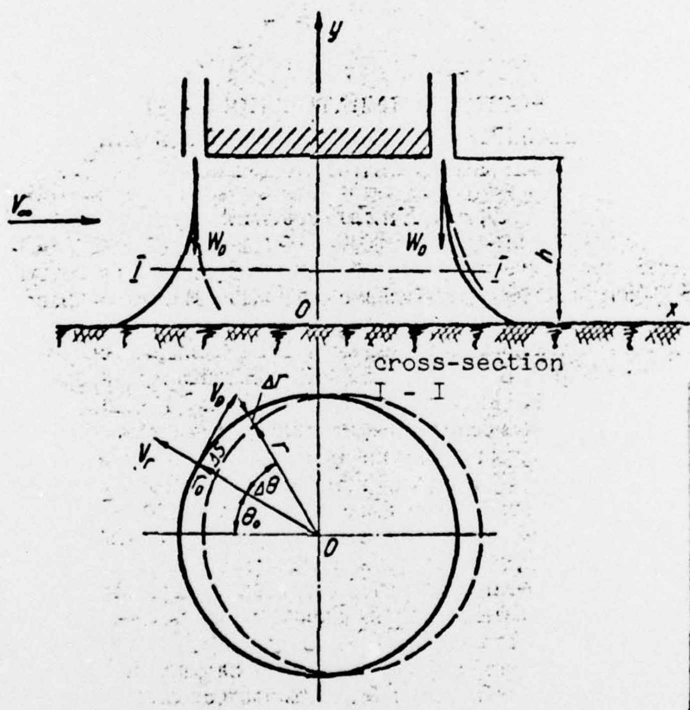

Figure 1.

Finally we have

$$\varphi = y(-W_0 + a_0 + a_1 r\cos\theta + a_2 r^2\cos 2\theta + \cdots + a_{10} r^{10}\cos 10\theta). \qquad (3)$$

For simplification, we omit value a_0. We determine the other unknown coefficients a_{1-10}, having used the method of least disturbances.

The combined horizontal velocity component during flow-around of an annular jet can be presented in the following form:

$$V = V\infty + v,$$

where v is a certain low disturbed velocity in the direction of the OX axis.

In the accepted coordinate system

$$V = V_\infty - v_r \cos\theta + v_\theta \sin\theta,$$

or

$$V = V_\infty - \frac{\partial\varphi}{\partial r}\cos\theta + \frac{1}{r}\frac{\partial\varphi}{\partial\theta}\sin\theta.$$

We take the Bernoulli equation for the midline of the jet in the incoming flow:

$$P_\infty + \rho\frac{V_\infty^2}{2} = P + \frac{\rho}{2}(V_\infty + v)^2.$$

v is small according to the condition and value v^2 can be ignored. Then /5

$$P - P_\infty = \rho V_\infty v \quad \text{and} \quad P = \frac{P - P_\infty}{\frac{\rho V_\infty^2}{2}} = -2\frac{v}{V_\infty}.$$

According to the accepted hypothesis, this latter value should coincide with the value of static pressure established on the surface of an infinite solid cylinder in the incoming flow.

One can represent the pressure distribution curve over the surface of the jet in the form of a set

$$\bar{P}(\theta) = \sum_0^{\kappa} A_\kappa\left(\frac{r}{R}\right)^\kappa \cos k\theta,$$

where R is the radius of the nozzle base and r is the distance from the midline of the jet to the axis of the vehicle.

We determine the unknown coefficients A_k, having solved the system of equations (3).

The experimental values $\bar{P}$ (Θ) of pressure distribution over the surface of an infinite solid cylinder are substituted in the right-hand parts of the system.

Assuming that the distribution of pressures will be similar in subsequent cross-sections of the jet height-wise, and having limited ourselves to five values of angle Θ (for example, Θ = 0; 45; 90; 135; 180°), we find the pressure coefficients $\bar{P}$ (Θ) in each cross-section according to the equation

$$\bar{P}(\theta) = A_0 + A_1\frac{r}{R}\cos\theta + A_2\left(\frac{r}{R}\right)^2\cos 2\theta + A_3\left(\frac{r}{R}\right)^3\cos 3\theta + A_4\left(\frac{r}{R}\right)^4\cos 4\theta. \quad (4)$$

The relationship r that enters into the latter formula can be determined using the results of a work [3]:

$$r = R\left[1 + \frac{h}{R}\left(1 - \frac{y}{h}\right)\right],$$

where h is the height of the nozzle above the surface;

y is a variable coordinate.

According to expression $\overline{P}(\theta) = 2\frac{v}{V_\infty}$, we shall have the following for the arbitrary height-wise cross-section of the jet

$$\overline{P}(\theta) = \frac{2y}{V_\infty}(a_1\cos^2\theta + 2a_2r\cos\theta\cos 2\theta + 3a_3r^3\cos\theta\cos 3\theta + \\ + \cdots + 10a_{10}r^9\cos\theta\cos 10\theta + a_1\sin^2\theta + 2a_2r\sin\theta\sin 2\theta + \\ + 3a_3r^2\sin\theta\sin 3\theta + \cdots + 10a_{10}r^9\sin\theta\sin 10\theta),$$

or

$$\overline{P}(\theta) = \frac{2y}{V_\infty}(a_1 + 2a_2r\cos\theta + 3a_3r^3\cos 2\theta + \cdots + 10a_{10}r^9\cos 9\theta = \\ = \frac{2y}{V_\infty}\sum_{n=0}^{10} nQ_nr^{n-1}\cos(n-1)\theta. \quad (5)$$

By comparing the values $\overline{P}$ (Θ) according to (4) and (5), we obtain the first five equations for determining the unknowns a_{1-10}. We write the five lacking equations on the basis of the following concepts. Velocity $W_{h,\Theta}$ in each height-wise cross-section of the jet is expressed by the relationship /6

$$W_{h,\theta} = \left(\frac{\partial\varphi}{\partial y}\right)_{h,\theta}.$$

Having written this condition for the five accepted values of angles Θ, we obtain a closed system of algebraic equations for determining coefficients a_{1-10}:

$$\sum_{n=1}^{10} na_nr^{n-1}\cos(n-1)\theta = \frac{V_\infty}{2y}\overline{P}(\theta); \\ \sum_{n=1}^{10} a_nr^n\cos n\theta = \Delta W(\theta). \quad (6)$$

The sequence of writing the system of equations should be the following. First one writes a system of equations for the cross-section closest to the nozzle edge, for example, for y = 0.9 h. Obviously, in this case one can assume that velocity W in the jet in the region from the cross-section of the nozzle to the cross-section y = 0.9 h does not change and remains equal to W along the entire edge of the jet, i.e., $\left(\frac{\partial\varphi}{\partial y}\right)_{0.9h\theta} = W_0$ and the right-hand parts of

equations (6) - (10) will be zero.

Upon transferring to the next cross-section, one already takes into account the change of velocity in the region from the cross-section of the nozzle to the previous cross-section. In the cross-section y = 0.7 h $\Delta W(\theta)_{0.7h} = W_{0.9h\theta} - W_0$.

This sequence of writing the equations makes it possible approximately to take into account the change of velocity in the jet proportional to height and to find the most accurate solution.

Having solved the system of equations (6) for the selected cross-sections and having obtained the expression for the function of the velocity potential, one can determine the characteristics of flow in the jet for each cross-section, i.e., velocity in the midline of the jet and deformation of the jet in the incoming flow. And one can find the component of resistance to movement of the ACV as well as the displacement of the center of pressure and change of the momentum characteristics of the vehicle according to the value of deformation of the jet by known methods [for example, see (5)].

Deformation of the jet in any cross-section along the height of the jet shall be determined according to the change of the velocity value in the region of the jet between the calculated cross-sections. For the selected coordinate system, we shall characterize deformation of the edge of the jet in two directions: as the radial Δr and circumferential ΔS. Radial deformation is calculated according to the formula

$$\Delta r = \left(\frac{\partial v_r}{\partial y}\right)_{\frac{\Delta h}{2}} \Delta h \Delta t,$$

where Δh is the minor edge of the jet - the distance between the calculated cross-sections;

Δt is the interval of time.

The local velocity of flow in the jet is characterized by the relationship $W_{h\theta} = \frac{\Delta h}{\Delta t}$, whence $\Delta t = \frac{\Delta h}{w_{h\theta}}$. But $W_{h\theta} = \left(\frac{\partial \varphi}{\partial y}\right)_{h,\theta}$, then finally

$$\Delta r_{h,\theta} = \left(\frac{\partial v_r}{\partial y}\right)_{\frac{\Delta h}{2}} \cdot \frac{(\Delta h)^2}{\left(\frac{\partial \varphi}{\partial y}\right)_{h,\theta}} = \left(\frac{\partial^2 \varphi}{\partial y \partial r}\right)_{\frac{\Delta h}{2}} \cdot \frac{(\Delta h)^2}{\left(\frac{\partial \varphi}{\partial y}\right)_{h,\theta}}. \qquad (7)$$

Similarly, one can write the circumferential deformation of the jet edge as follows: /7

$$\Delta s_{h,\theta} = \left(\frac{1}{r}\frac{\partial^2 \varphi}{\partial y \partial \theta}\right)_{\frac{\Delta h}{2}} \frac{(\Delta h)^2}{\left(\frac{\partial \varphi}{\partial y}\right)_{h,\theta}}. \qquad (8)$$

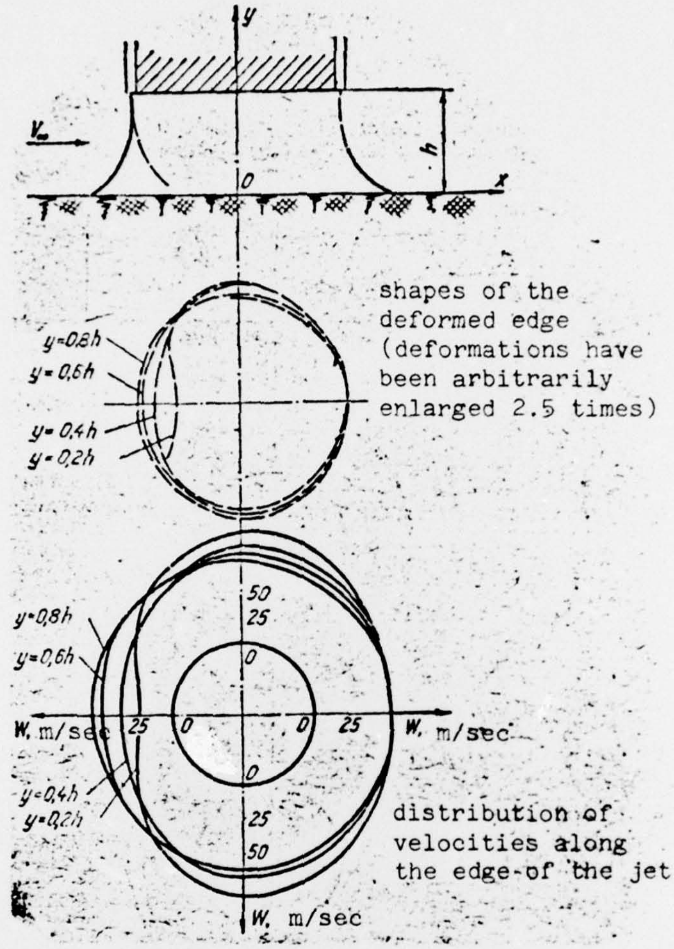

Figure 2.

Deformation of the jet contour along the height and edge of the jet is determined according to formulas (7) and (8).

Figure 2 gives the results of calculating the effect of the incoming flow on characteristics of a nozzle type ACV with the following parameters, as an example: nozzle radius R = 2500 mm, hovering height h = 1000 mm, discharge velocity of the jet from the nozzle W_0 = 60 m/sec, velocity of the incoming stream V_∞ = 20 m/sec.

As is apparent from the cited data, the results of the calculation do not contradict the physical nature of the phenomenon. The shape of the midline of the jet in the central cross-section corresponds in appearance to the data of visual investigations [6].

In practice, deflection of the jet from the vertical at a certain angle γ toward the axis of the vehicle is employed in ACV and the shape of the jet changes with respect to height: it is conical in the initial region and then /8
changes into a cylindrical one and flows over a screen. The method of calculation examined above can also be used in this case. It is merely necessary to introduce the values of pressure coefficients for the cone and the corresponding values R and r into the system of equations. The latter can be determined according to the data of a work [3] . When t < h, value r is determined according to the formula

$$r = R\left\{1 - \frac{h}{R}\frac{1}{\sin\gamma_c}\left[1+\frac{y}{h}(1+\sin\gamma_c)-1\right]^2 + \cos\gamma_c\right\}. \quad (9)$$

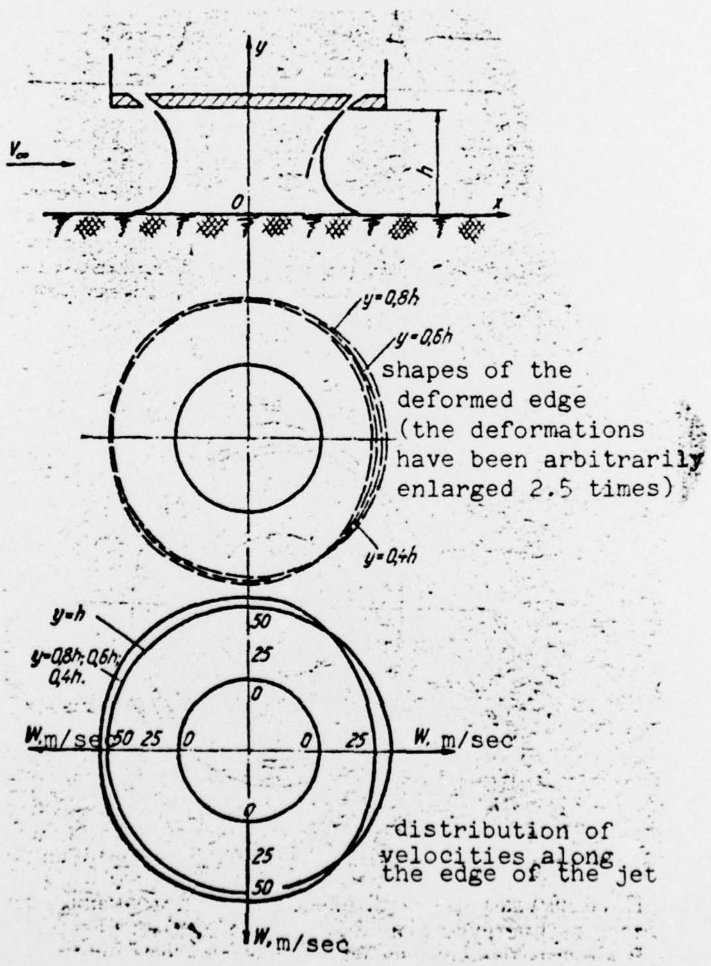

Figure 3.

The function of the velocity potential for the conical region of the jet also acquires a somewhat altered appearance:

$$\varphi = y(-W_0 \cos\gamma_c + a_1 r \cos\theta + a_2 r^2 \cos 2\theta + \cdots + a_{10} r^{10} \cos 10\theta) + \\ + W_0 r \sin\gamma_c. \qquad (10)$$

Figure 3 gives the results of calculating a conical jet for the same initial parameters: $R = 2500$ mm, $h = 1000$ mm, $W_0 = 60$ m/sec, $V_\infty = 20$ m/sec and $\gamma_c = 30^\circ$.

Hence, when the relationship of velocity of the incoming flow V_∞ and the /9
discharge velocity of the jet from the nozzle W_0 is $\frac{V_\infty}{W_0} = 0.333$, no significant change in the edge shape of either the cylindrical or the conical jets occurs. The distribution of flow velocities in the jet along its edge changes slightly, and consequently the aerodynamic characteristics of the air cushion vehicle also do not change. When the velocity of the incoming flow is equal to the discharge velocity, the parameters of the jet and the shape of its edge change more. The midline of the jet in cross-section of the screen is bent beneath the bottom of the vehicle.

A redistribution of velocities along the edge of the jet is also observed: the flow velocity in the jet decreases on the high pressure side and increases in rarefaction zones. The latter obviously leads to a change in the distribution of pressure in the region of the air cushion and to the appearance of diving momentum. This conclusion is confirmed by full-scale and experimental tests [6]. The comparative evaluation of the results of the calculation shows that the conical jet screen is most resistant to deformations and change of aerodynamic characteristics in flight.

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